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DESIGN FOR A TAPERED ELEMENT OSCILLATING
MICROBALANCE SENSING SURFACE Final Report
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A TEMPERATURE CONTROL DESIGN FOR
A TAPERED ELEMENT OSCILLATING MICROBALANCE
SENSING SURFACE

FINAL REPORT
CONTRACT # 956284

SEPTEMBER 1982



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ABSTRACT

A design study is presented which shows that a Tapered Element Oscillating Microbalance (TEOM) can be adapted for temperature control under space application by mating with multistage thermoelectric coolers in such a way that an integral structure evolves. The control of the temperature of the sensing surface can be achieved in a number of ways. An indirect method which uses a measurement of the absorbed power is recommended. The design goals can be met if a relaxation of the power requirement can be considered.

1. INTRODUCTION

The Tapered Element Oscillating Microbalance (TEOM) has been used in numerous applications where the continuous measurement of small masses such as particulates on a real time basis is of the essence.

Since with a TEOM the mass measurement is based on inertia, not on gravitational forces, the instrumentation is suitable for space application. Normally mass measurements are performed at a constant temperature. In the presently intended space application, however, a choice of sensing surface temperatures over a wide range of temperatures is required.

It is the purpose of this report to assess the adaptability of the TEOM system to this requirement under space conditions, i.e. vacuum and a varying radiative background with and without solar radiation, and the development of a design for the implementation of a temperature control of the sensing surface of a TEOM.

2. TECHNICAL DISCUSSION

2.1 Mechanical and Thermal Design Requirements

The description of the TEOM, its structure, operation, and underlying theory is given in the Appendix. The presently considered configuration is described there under "Series 2000". For the present application, the sensing surface is envisioned as an aluminum disc for the following reasons:

- (A) favorable optical properties
- (B) light weight
- (C) excellent thermal conductance
- (D) structural stability especially in a workhardened sample.

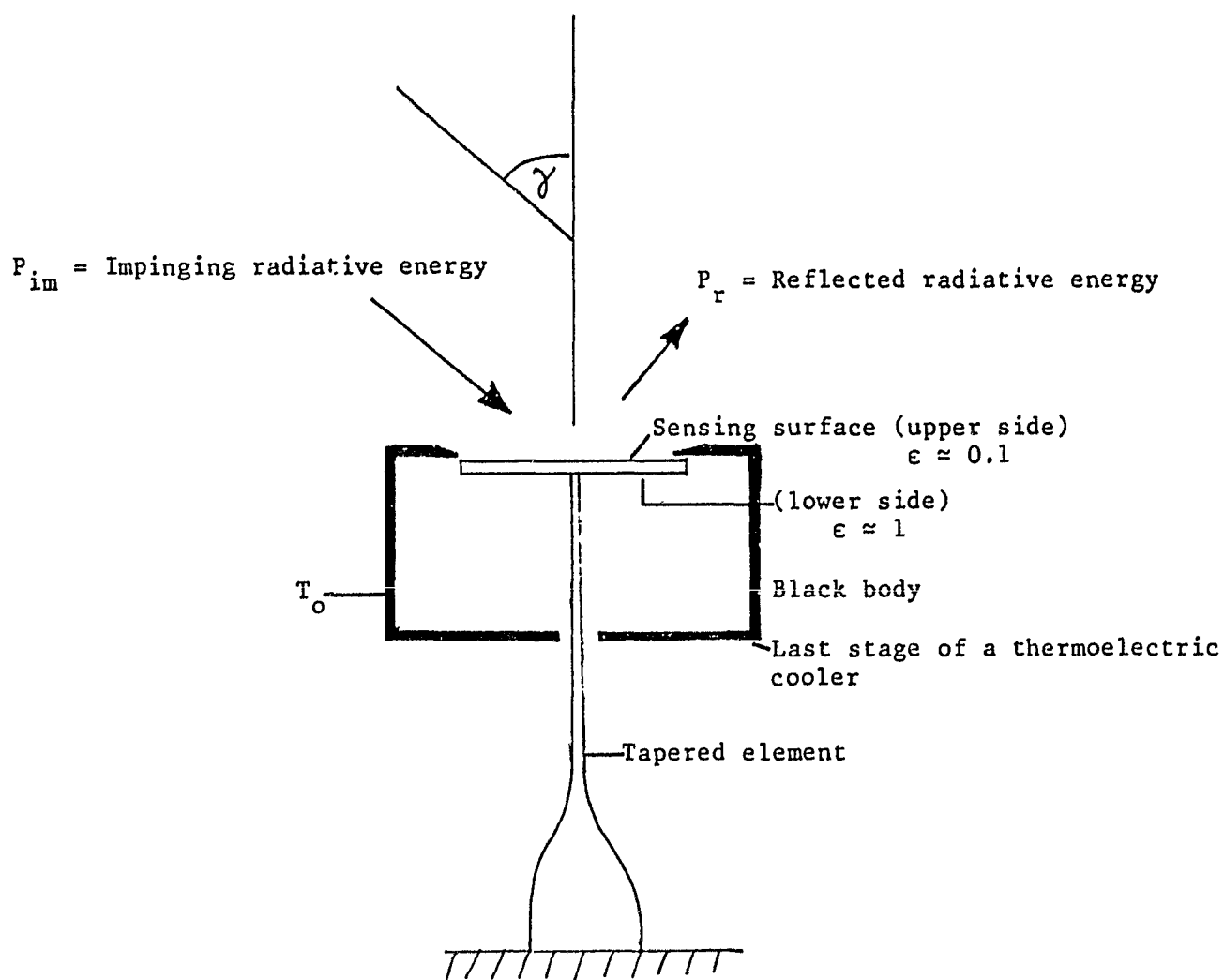
This metal disc is attached permanently to the tapered element which, being fabricated of a material with low thermal conductance, eliminates the possibility of effectively controlling the temperature of the sensing surface by conductive heat transfer through the tapered element.

The only effective means of a temperature control in vacuum is therefore through radiative heat transfer to the sensing surface. In this case the low thermal conductivity of the tapered element can be used to advantage and it can be stated as a design goal:

- (1) to thermally isolate the sensing surface from the tapered element
- (2) to reduce the absorption of solar radiation of the upper side of the sensing surface (looking into space) to a minimum
- (3) to maximize the radiative heat transfer of the lower side of the sensing element (which is attached to the tapered element) to the black body heat exchanger.

The configuration envisioned is shown in Figure 1. The upper side of the sensing surface is highly reflective to solar radiation, while the lower side is treated to provide a high emission in the infrared part

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$$\Delta P = P_{im} - P_r - P_e$$

P_{im} = impinging power

P_r = reflected power

P_e = emitted power

FIGURE 1. PRINCIPLE CONFIGURATION FOR RADIATIVE
HEAT EXCHANGE INVOLVING THE TEOM
SENSING SURFACE

of the spectrum. By controlling the wall temperature, T_o , of the black body which is placed on the lower side of the sensing surface, the temperature of the sensing element can be varied for a fixed value of the absorbed power, P_{abs} . If one neglects for the moment the conductive heat transfer via the tapered element, one can make the following statement. For each value of the net absorbed solar power, ΔP ($\Delta P = P_{abs} - P_{em}$, where P_{abs} is the absorbed power and P_{em} is the emitted power and where ΔP also depends on the angle γ), and each value T_o of the black body, there exists a unique temperature, T_s , of the sensing surface which depends only on the optical properties, ϵ_{up} and ϵ_{down} , of the upper and lower sides of the sensing surface, respectively:

$$T_s = T_s (T_o, \Delta P, \epsilon_{down}). \quad (1)$$

Because of this unambiguous relationship, one can state that there exists also a relation of the form:

$$T_o = T_o (T_s, \Delta P, \epsilon_{down}). \quad (2)$$

While Equation (1) has always a steady state solution in the sense that for any given value of P_{abs} and any wall temperature, T_o , the sensing element will always acquire a well defined temperature, T_s , the same does not hold true with independent variables T_s and P_{abs} . Indeed, P_{abs} and T_s cannot be chosen at will but are subject to limitations. In fact, one can name for any given value of P_{abs} a substrate temperature, T_s , for which no wall temperature $T_o > 0$ exists to satisfy the energy transfer relations.

Furthermore one must keep in mind that the lower limit of the wall temperature T_o which can be achieved in a given device is due to the properties of the thermoelectric cooler and by the available

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electric power expended for cooling. Thus the practical limit for T_o sets also a lower limit for the T_s values to chose from. The lower limit for T_s depends also greatly on ΔP .

It is the purpose of the next section to explore this limitation for a practical case as a basis for the assessment whether or not radiative cooling of the sensing surface of the TEOM is feasible or not.

2.2 Limitations to Radiative Cooling

In the statement of work, the following requirements are expressed:

- (1) The temperature of the sensing surface shall be variable between

$$-65^{\circ}\text{C} \leq T_s \leq 60^{\circ}\text{C} \quad (3)$$

within a room temperature environment under vacuum and full solar exposure.

- (2) The available electrical power, P_{el} , to achieve steady state temperatures within the limits stated above is

$$P_{el} = \begin{cases} 3 \text{ Watt (average)} \\ 7 \text{ Watt (peak)}. \end{cases} \quad (4)$$

While the upper temperature limit can be reached with merely a small fraction of the available electrical power simply by inverting the polarity of a thermoelectric cooler, the achivement of the lower limit requires some scrutiny.

According to the literature which is available on the performance of thermoelectric coolers, it is quite obvious that a cooling down from room temperature to 208°K requires a thermoelectric cooler with several stages (at least three, probably five). It also becomes obvious

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very quickly that the wall temperature, T_o , of the black body must be held considerably below this temperature to enable an efficient radiative heat transfer. The calculations are simply based on the relation that the emitted power is

$$P_e = \epsilon \sigma T^4 . \quad (5)$$

In order to limit the calculations to a manageable size and still obtain enough information, a number of simplifications have been introduced. Two sets of ϵ values have been selected:

$$\left\{ \begin{array}{l} \epsilon_{up} \approx 0.1 \\ \epsilon_{dwn} \approx 1.0 \end{array} \right. \quad \left\{ \begin{array}{l} \epsilon_{up} \approx 0.05 \\ \epsilon_{dwn} \approx 0.9 \end{array} \right. \quad (6)$$

and two values for T_o (at the last stage of the thermoelectric cooler) were chosen which are realizable within the power limitations stated above:

$$\left\{ \begin{array}{l} T_o = 173^\circ K \\ T_o = 193^\circ K \end{array} \right. \quad (7)$$

A simple calculation shows, however, that a configuration as seen in Figure 1 does not permit the temperature T_s of the sensing surface to reach the lower limit required. There the area A_1 exposed to the solar radiation (with ϵ_1) equals the area A_2 (with ϵ_2). For this reason the efficiency of radiative cooling must be enhanced by using the configuration shown in Figure 2.

The lower surface with (ϵ_2 , A_2) has been extended around the rim of the sensing surface with a width, Δr , thus shrinking the upper surface (A_1 , ϵ_1) in size and therefore in the uptake of radiative energy.

Defining 'a' as the ratio between the power dissipating surface area A_2 and absorbing area A_1 :

$$a = \frac{A_2}{A_1} , \quad (8)$$

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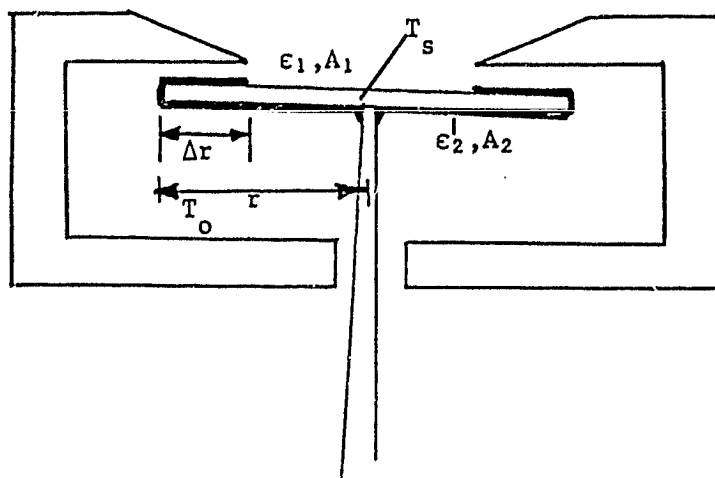


FIGURE 2. THE COOLING ARRANGEMENT FOR THE
SENSING SURFACE OF A TEOM

one finds for $\Delta r/r$ the following relation:

$$\frac{\Delta r}{r} = 1 - \sqrt{1 - \frac{a-1}{a+1}} \quad (9)$$

Some values are shown in Table 1. For these values and the indicated ϵ and T_o values, both ΔP (in mW) and T_s (in $^{\circ}\text{K}$) are listed in Table 1.

Table 1. Relation between 'a', $\Delta r/r$, and Values for ΔP and T_s for Given ϵ and T_o Values.

				$a = \frac{A_2}{A_1}$	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
				$\frac{\Delta r}{r}$	0	0.106	0.184	0.244	0.293	0.333	0.378	0.397
T_o	ϵ_1	ϵ_2										
173	0.1	1.0	$\Delta P(\text{mW})$		15	13.64	12.7	12.28	11.57	11.18	10.87	10.61
			$T_s(^{\circ}\text{K})$		243	220.7	211.7 ↑	206.1	201.7	198.3	195.8	193.7
193	0.1	1.0	$\Delta P(\text{mW})$		17.26	16.31	15.68	15.23	14.91	14.64	14.43	14.24
			$T_s(^{\circ}\text{K})$		242.8	230.8	223.1	218.1	214.7	212.0	210.0	208.5 ↑
193	0.05	0.9	$\Delta P(\text{mW})$		11.13	11.17	11.19	11.20	11.22	11.23	11.23	11.23
			$T_s(^{\circ}\text{K})$		228.7	216.8	211.6	208.5 ↑	206.2	204.5	203.2	202.1

The arrows in Table 1 locate the $\Delta r/r$ value which is necessary to achieve the required cooling of the sensing surface. One can conclude from the calculated values that a black body temperature between 173°K and 193°K will lead to the required cooling of the sensing surface as long as the values for absorptivity in the visible part of the spectrum can be kept between 0.1 and 0.05.

A thermoelectric heat pump with several stages which lowers the temperature by 100°K can indeed keep the sensing surface at -65°K . However, the quoted allowance for the electrical power will not be sufficient. A higher power consumption (at least tripled) must be anticipated.

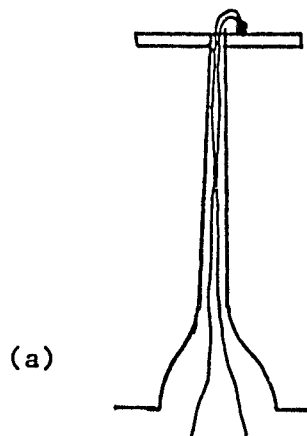
2.3 Temperature Sensing Requirements

While in the previous section a cooled black body of wall temperature T_o was shown to achieve the radiative heat transfer of energy away from the sensing surface of steady state temperature T_s , it was implicitly assumed that the pertinent temperatures are known. No problem exists for the determination of the wall temperature, T_o , but the determination of T_s , however, presents a major problem. The knowledge of T_s is required for a feedback system to control T_s .

Techniques for determining T_s are shown in Figure 3. Comments are required for each case.

- (a) The attachment of a thermocouple to the sensing surface, as shown in Figure 3a, results in a severe damping loss of the vibrating TEOM and with it a loss of sensitivity. Extremely fine thermocouple wires have been used in the past to obtain direct measurements of the temperature of the sensing surface. We do not believe, however, that the loss of sensitivity incurred would be tolerable for the present application.
- (b) An improvement can be expected when the conductive path of the thermocouple is evaporated onto the tapered element with a short thermocouple attached to the conductive pathways, as indicated in Figure 3b. In this case, damping

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Thermocouple through hollow tapered element and attached to sensing surface

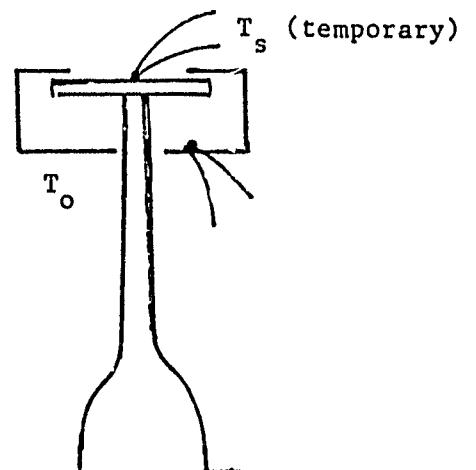
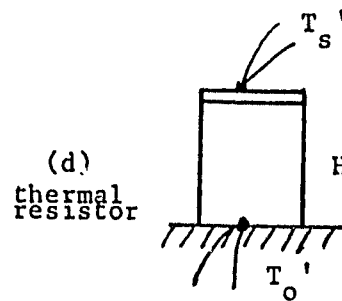
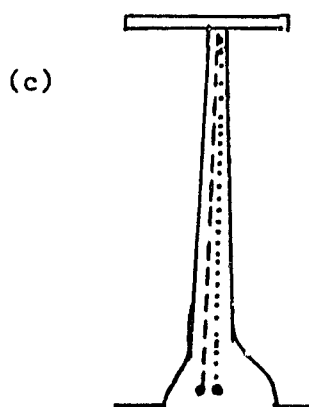
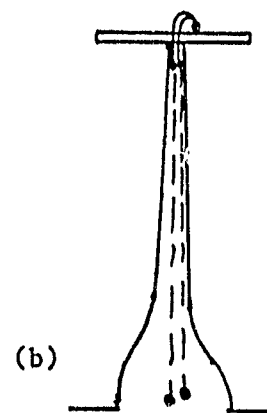


FIGURE 3. TECHNIQUES FOR DETERMINING T_s .

losses and addition of mass can be significantly reduced.

- (c) Instead of attaching a clipped thermocouple to the sensing surface, a thermocouple can be generated by evaporation of an appropriate materials pair. This method, although attractive, has the distinct disadvantage of requiring a substantial development effort. Damping losses and mass addition would be negligible.
- (d) Finally a method shall be described where T_s is not measured directly but uses a reference surface for its determination. The principle is shown in Figure 3d, where the calibration procedure is illustrated.

The calibration for the technique in Figure 3d needs further explanation. Since a thermocouple is attached temporarily to the sensing surface, T_s can be measured directly as a function of T_o for a fixed radiation. The same radiation impinges on a neighboring surface which has the same optical properties as the sensing surface but which is attached so a thermal resistor of known thermal conductivity and thickness, H . Under the influence of the impinging radiation, a linear temperature gradient is built up within the thermal resistor which is

$$\text{grad } \Delta T' = \text{grad } (T_s' - T_o') = \frac{\Delta T'}{H} \quad (10)$$

The absorbed power is

$$\Delta P' = k \text{ grad } T' = k \cdot \frac{\Delta T'}{H} \quad (11)$$

where k is related to the thermal conductivity of the resistor. In order to make $\Delta P'$ the same as the power absorbed by the sensing surface of the TEOM, one has to adjust the temperature T_o' of the base in such a way that

$$T_s' = T_s . \quad (12)$$

Under these circumstances

$$\Delta P' = \Delta P . \quad (13)$$

This furnishes one calibration point

$$T_s = T_s (\Delta P, T_o, \epsilon_{up}) . \quad (14)$$

Other calibration points are obtained

(a) by varying T_o at a fixed radiation

and

(b) by varying the radiation but keeping T_o fixed. Now the temporary thermocouple on top of the sensing surface is removed, and the TEOM is free to vibrate and perform the task of mass deposition measurement. However, a direct measurement of T_s is no longer available.

If a certain value, T_s , for the operation of the TEOM sensing surface has been chosen, a number of steps are to be taken to adjust T_o to the appropriate value in such a way that for the presently impinging radiation the temperature of the sensing surface is indeed the chosen temperature, T_s .

(STEP 1) Vary T_o' to a value that for the given radiation T_s' equals the prescribed temperature T_s .

(STEP 2) From the values T_s' , T_o' and the known thermal conductivity of the reference thermal resistor, a determination of ΔP can be made.

(STEP 3) Use the calibration data to determine the unique value T_o which belongs to the chosen value of T_s and the value for ΔP found in Step 2.

(STEP 4) Adjust T_o to this value.

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Although T_s is not measured directly in this procedure, the reference surface picks up the energy transfer from the impinging radiation and the calibration data allow for the determination of the black body wall temperature T_0 which, under the present circumstances, produces the desired temperature of the sensing surface.

Note that at all times $T_s = T_s'$, i.e. the reference surface will experience the same deposition as the sensing surface and therefore any changes of the optical properties during operation remain identical and do not lead to an error in T_s .

As one can notice, the determination and the control of T_s becomes increasingly complex in the subsequent examples shown from a through d in Figure 3. From a systems standpoint, the last example of an indirect measurement of T_s appears the most desirable, since no compromise in respect to TEOM sensitivity has to be made and the full potential of the TEOM can be brought to bear.

2.4 Overall Design

So far it has been shown that in case of a negligible thermal conductance along the tapered element of a TEOM, the sensing surface can indeed be cooled to the required value of -65°C if some concession can be made concerning the available electrical power.

All the considerations, however, were limited to the last stage of a thermoelectric cooler and no consideration was given to the task how a thermoelectric cooler with its pyramid-like structure can be mated with the TEOM's mechanical structure. This could present a real problem were it not for the fact that the pyramid structure of the thermoelectric cooler can be slightly modified to create a chamber

in its center where the tapered element can be placed. Such an approach is shown in Figure 4.

A double pyramid with a "burial chamber" houses the TEOM. Note that in this design the entire TEOM structure is cooled and that in this way thermal gradients along the tapered element are being minimized. Both pyramids are attached to a base plate which can serve as a mechanical mount and at the same time serves as a heat conductor to carry away the energy given off by the thermoelectric coolers. One can also notice a number of heat shields indicated in Figure 4 by dashed lines. These heat shields reduce the heat loss through radiation from the surroundings. Also shown is the thermocouple which measures T_o .

Included in Figure 4 is the design of a reference cell and the thermocouples to measure T_s' , T_o' .

3. CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from this study that the TEOM and thermoelectric cooling modules can indeed be modified to be mated into an integral structure which can achieve the design of objectives, provided the power requirement can be relaxed. It is recommended to control the value of T_s by the indirect method through a reference surface as outlined above.

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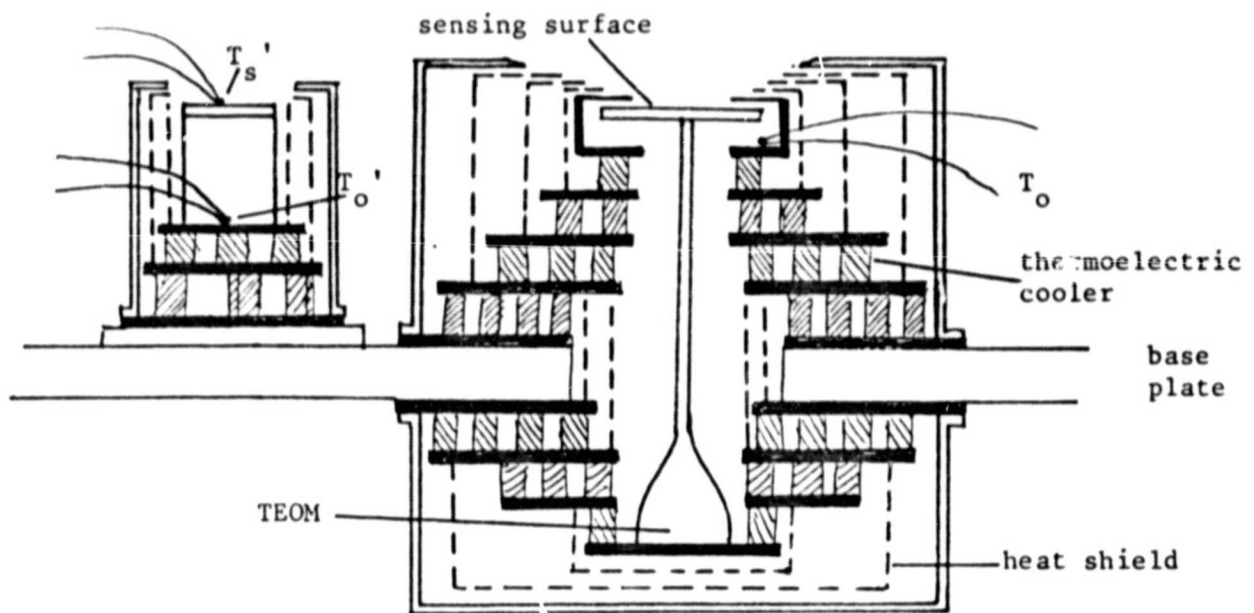


FIGURE 4. OVERALL STRUCTURE OF THE TEOM WITH A
TEMPERATURE CONTROLLED SENSING SURFACE.

APPENDIX

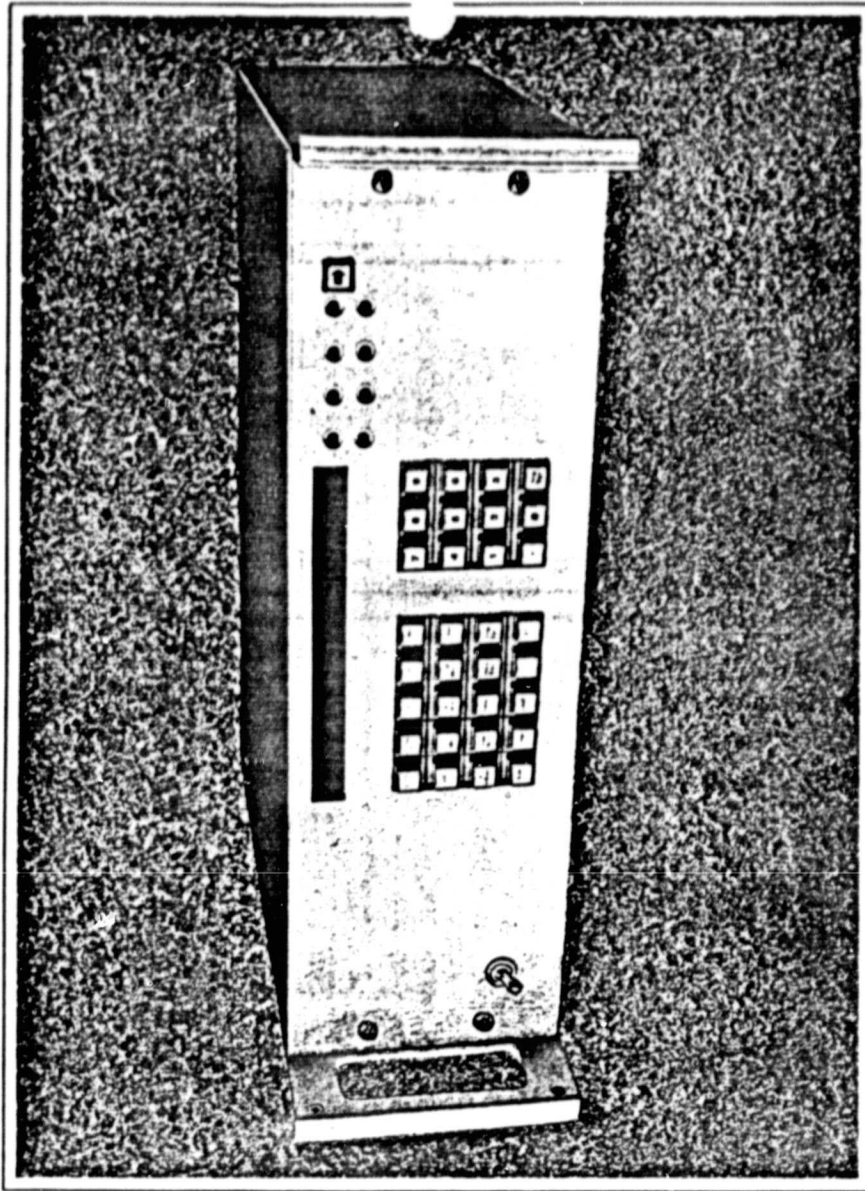
TEOM*

PARTICULATE MASS MONITORING SYSTEMS

Real-time evaluation of:

- Air Pollution
- Dust Concentration
- Diesel Exhaust
- Smoke Stack Emission
- Vapor Deposition
- Outgassing of Materials

*TEOM - Tapered Element Oscillating Microbalance is a patented device.



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AN INTRODUCTION TO THE TEOM

WHAT IS A TEOM?

TEOM stands for Tapered Element Oscillating Microbalance. The active element of the TEOM consists of a tapered tube constructed of a material with a high mechanical quality factor. This tube is firmly mounted at the wide end, while the narrow end supports a substrate. The substrate can be composed of virtually any material and can take on a variety of shapes. The TEOM is set into oscillation by a feedback system. A mass change on the substrate is reflected by a frequency change of the TEOM.

HOW DOES THE TEOM FUNCTION?

The oscillatory motion of the active element is converted into an electrical signal by an LED-phototransistor combination. The natural frequency of the TEOM, as monitored by this signal, changes in relation to the mass change on the substrate. This allows for an accurate, highly sensitive mass measurement in real time.

HOW CAN THE TEOM BE USED?

A TEOM is an optimal device for many types of mass monitoring. For particulate measurements, the substrate on the TEOM can take the form of an exchangeable filter cartridge. Particulate-laden air is drawn through the filter, where the particles are collected. This set-up allows for the real-time measurement of air pollution, diesel exhausts, and smokestack emissions. A multi-stage instrument can determine particulate mass concentration as a function of size. Substrates in the form of discs are used to measure mass deposition rates as well as outgassing and/or sublimation rates of diverse materials at different temperatures.

HOW DOES THE TEOM DIFFER FROM OTHER PARTICULATE MASS MEASURING SYSTEMS?

The measurement of particulate concentrations in air has been attempted with a number of widely varying techniques. Each of these has its shortcomings. Optical instruments and β -attenuation monitors do not measure mass directly. QCM's rely on impaction, have a limited dynamic range, and cannot function with substrates other than their own crystal surface. While gravimetrically evaluated filter samplers provide direct mass measurement, they lack real-time capability and sensitivity. The TEOM provides a direct measure of mass changes with great sensitivity and accuracy in real time.

WHY SHOULD YOU USE A TEOM?

The TEOM measures mass directly in real time. Its simplicity, ruggedness, nearly maintenance-free operation and adaptability to hostile environments makes it a valuable tool under demanding conditions. The automatic data collection, storage and documentation controlled by a built-in microprocessor allow the TEOM to run unattended over long periods of time. This is also made possible by the great dynamic range (10^6) of the TEOM sensor. The device can be interfaced easily with most computers. TEOM instrumentation represents the latest in the state of the art of real-time mass monitoring.

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SERIES 1000 TEOM's are characterized by the use of an exchangeable filter cartridge as the substrate. The accumulation of particulates suspended in a gas is achieved by pumping the gas through the filter, where the particulates are deposited. The filtered gas then exits the TEOM at the fixed end. Applications for this configuration: air pollution monitoring; health maintenance systems in coal mines and other dusty environments; monitoring of smokestack emissions; and as an analytical tool in the measurement of diesel engine exhaust.

SERIES 2000 TEOM substrates are in the form of a permanently affixed table. This series is particularly useful in vacuum applications, such as thin film deposition monitoring. Hundreds of milligrams of material can be deposited on the substrate before cleaning. Utilizing a sticky coating on the table, the masses of single particles (down to 10⁻¹⁰ g) can be determined. Table substrate TEOM's have also been developed for space missions. The Series 2000 TEOM is an indispensable tool for the investigation of the outgassing and sublimation properties of materials.

SERIES 3000 TEOM's differ from those of the 2000 Series due to the exchangeability of the substrate, which can take on many forms. For smokestack monitoring, a cup-like substrate is used in which the particles extracted by a cyclone are collected. The cup configuration is also ideally suited for the investigation of granular materials whose outgassing and sublimation rates are measured as a function of temperature.

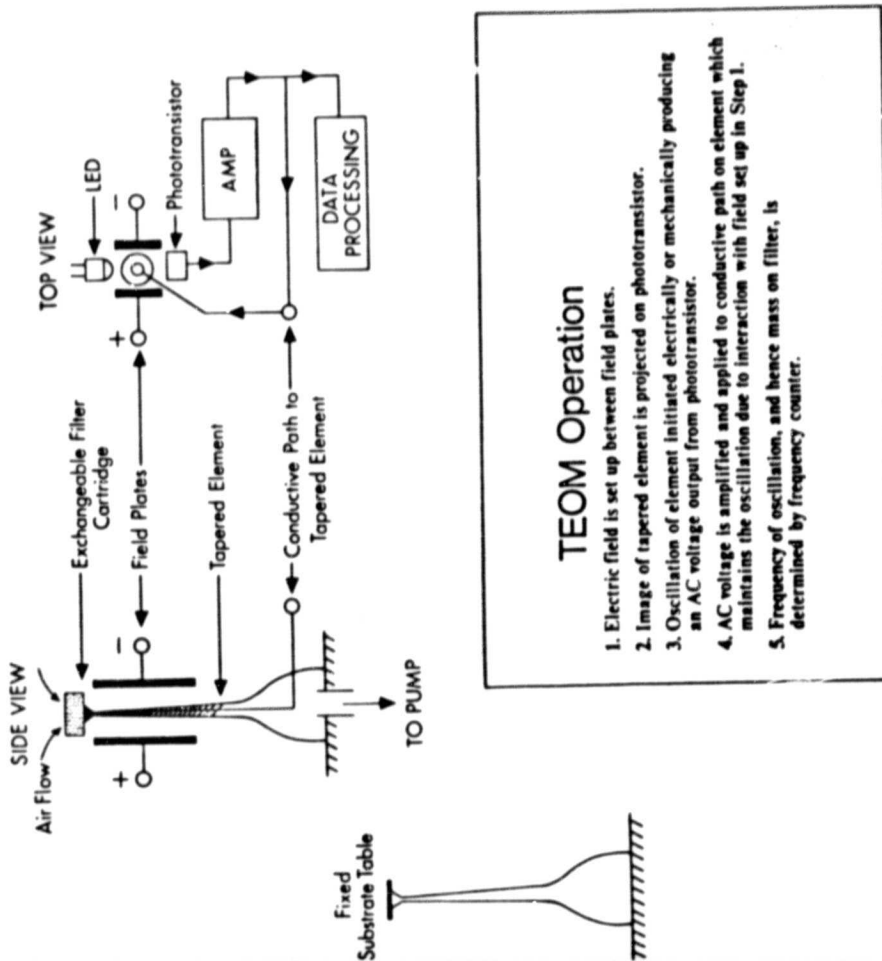
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Exchanged
Substrate C

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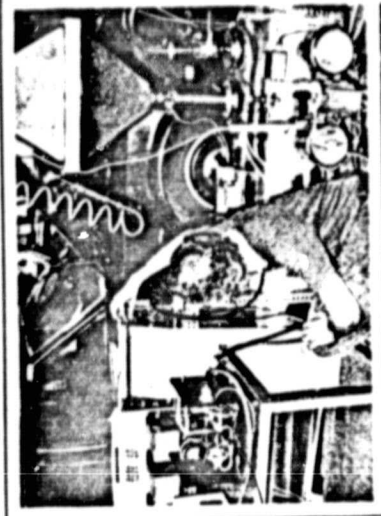
Temperature ranges of various TEOM applications

-260°C to -30°C	-30°C to +60°C	+60°C to +500°C
	AIR POLLUTION HEALTH MAINTENANCE SYSTEMS DIESEL EXHAUSTS (Dilution Tunnel)	DIESEL EXHAUSTS (Direct)
	SUBLIMATION AND OUTGASSING STUDIES VACUUM AND/OR GRAVITATION-FREE APPLICATIONS SINGLE-PARTICLE COLLECTION MATERIALS DEPOSITION CONTROL DIFFERENTIAL THERMAL ANALYSIS SMOKESTACK MONITORING	

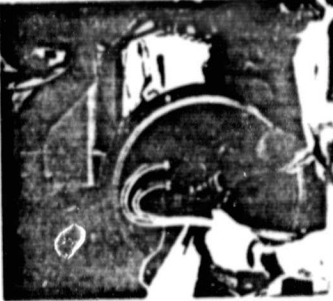


NOTE: The R&P Company would be pleased to discuss with you any additional applications which might be needed for your specific situation. TEOM systems can be customized to meet your particular requirements.

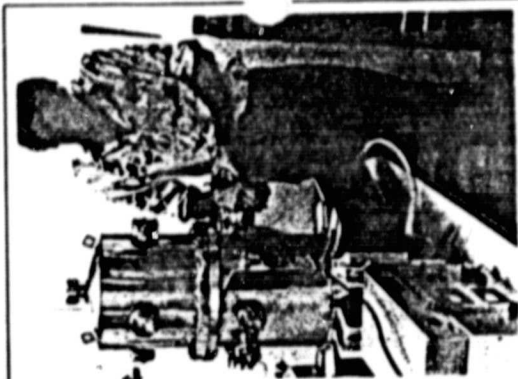
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Diesel exhaust monitoring with TEOM instrumentation built for Cummins Engine Company. Shown under test at Automotive Emissions Laboratories of New York State Department of Environmental Conservation



Materials outgassing study with TEOM instrumentation at Martin Marietta Aerospace, Denver, CO



Particulate flux monitoring in a vacuum with a TEOM for Jet Propulsion Laboratory



Multistage TEOM Smokestack Monitoring System at Sandia National Laboratories, Livermore, CA

for further inquiries contact:

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scientific instrumentation & consulting

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EXPERIMENTAL RESULTS

The performance of the TEOM has been documented in a number of publications. A sampling of experimental results is shown in the adjacent panels. Figure 1 illustrates results from ambient measurements collected by a Series 1000 TEOM. In Figure 2, a Series 2000 TEOM is used to ascertain the sublimation rate of a solvent. The data shown in Figure 3 was gathered by a Series 1000 TEOM smokestack monitor. Figure 4 shows results from a TEOM diesel exhaust monitor sampling from a dilution tunnel.

THEORY OF OPERATION

The TEOM frequency can be described with two parameters: the restoring force constant of the tapered elastic element, K , and the effective mass, m , consisting of the mass of the substrate, m_s , the effective mass of the tapered element, m_o , and the mass loading, Δm .

$$m = m_s + m_o + \Delta m \quad (1)$$

The relation between these quantities is given by the expression

$$4\pi f^2 = \frac{K}{m} \quad (2)$$

or

$$f^2 = \frac{K_o}{m} \text{ with } K_o = \frac{K}{4\pi^2} \quad (3)$$

MASS MEASUREMENTS

If the TEOM is oscillating at the outset with the frequency of f_1 and exhibits the frequency f_2 after an unknown mass uptake, Δm can be obtained as a function of f_1 , f_2 and K_o . It is:

$$\Delta m = K_o (1/f_2^2 - 1/f_1^2) \quad (4)$$

Note that Equation 4 is independent of the substrate mass, m_s , and the effective mass of the oscillating tapered element, m_o .

MASS RESOLUTION

The mass resolution δm and the mass m in Equation 1 are empirically related by

$$\frac{\delta m}{m} = 10^{-6} \quad (5)$$

The relation indicates that the lighter the total mass, the higher the mass resolution of the instrument. By appropriate dimensioning of the TEOM, virtually any mass range can be accommodated. Presently, the lower limit for the mass resolution is $\delta m = 10^{-12}$ g.

DYNAMIC RANGE

From Equations 1 and 5 it is apparent that as long as the mass loading, Δm , is smaller than the substrate mass plus the effective mass of the tapered elastic element, the sensitivity of the TEOM remains virtually unchanged. Therefore, the dynamic range (from mass resolution δm to mass loading Δm before a loss of resolution by a factor of two is incurred) is:

$$\frac{\Delta m}{\delta m} = 10^6 \quad (6)$$

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OF POOR QUALITY

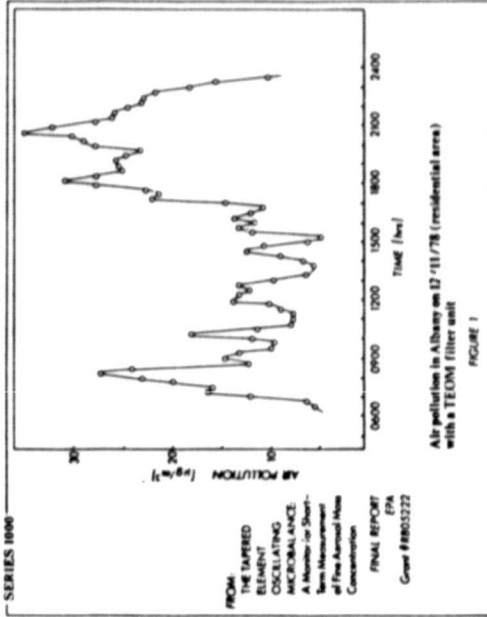


FIGURE 1

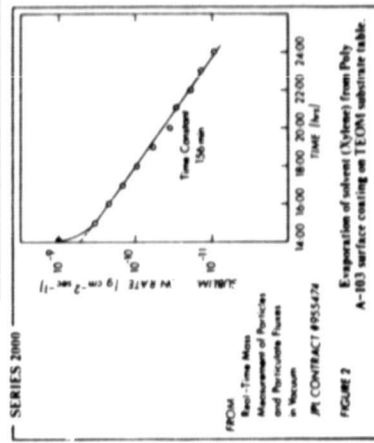


FIGURE 2

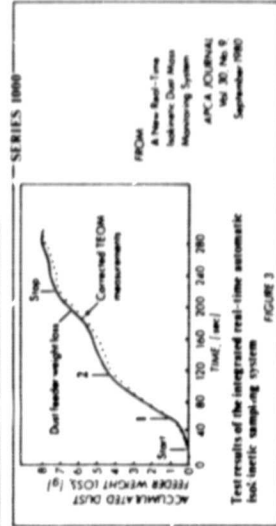


FIGURE 3

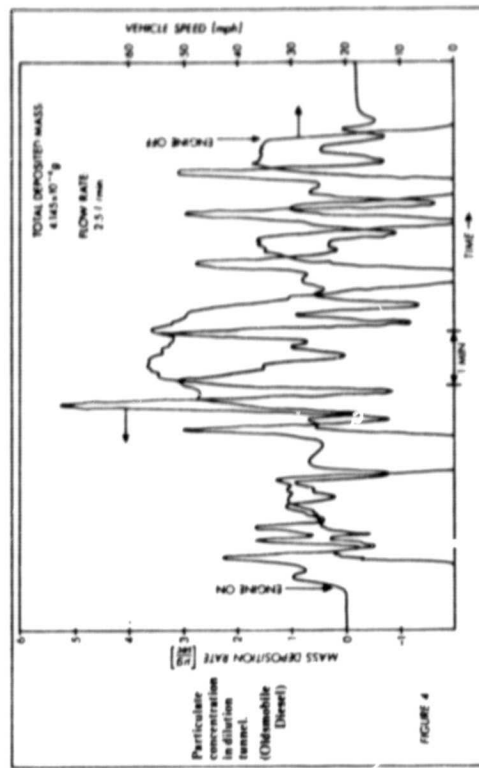


FIGURE 4

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